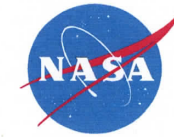


National Aeronautics and Space Administration

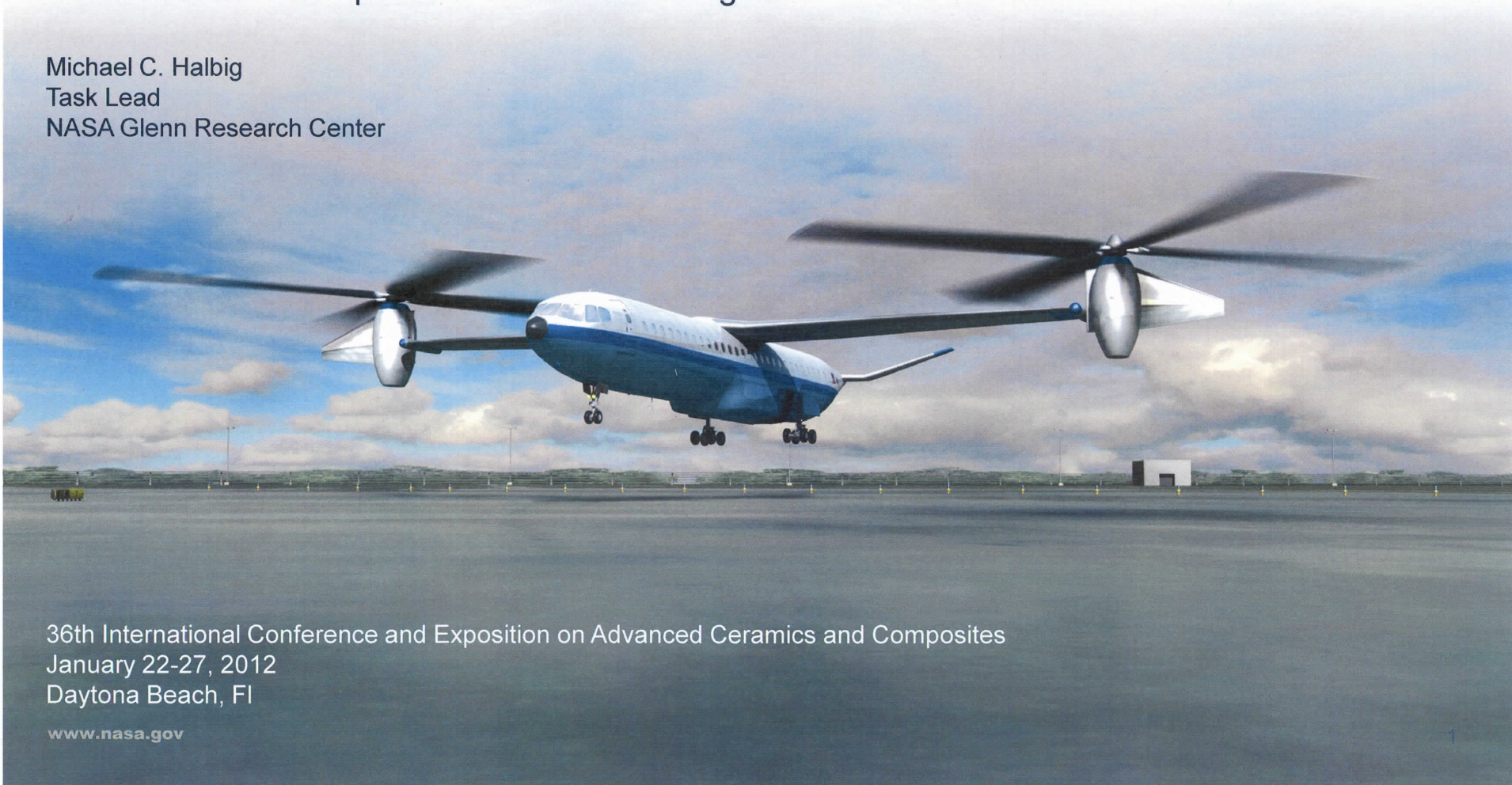


Fundamental Aeronautics Program

Subsonic Rotary Wing Project

Ceramic Matrix Composites for Rotorcraft Engines

Michael C. Halbig
Task Lead
NASA Glenn Research Center



36th International Conference and Exposition on Advanced Ceramics and Composites
January 22-27, 2012
Daytona Beach, FL

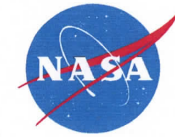
www.nasa.gov

Acknowledgements



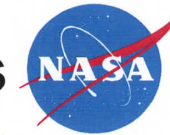
- The team for the CMC airfoil task includes:
 - Ram Bhatt, Army Research Laboratory, Cleveland, OH
 - Jay Singh, Ohio Aerospace Institute, Cleveland, OH
 - Craig Smith, Ohio Aerospace Institute, Cleveland, OH
 - Jim DiCarlo, NASA Glenn Research Center, Cleveland, OH
 - Jerry Lang, NASA Glenn Research Center, Cleveland, OH
 - Sai Raj, NASA Glenn Research Center, Cleveland, OH
 - Dongming Zhu, NASA Glenn Research Center, Cleveland, OH

Outline



- Introduction and Background Information
 - SRW Program's LCTR Vehicle Concept and the CMC Airfoil Effort
 - Airfoil Challenges
 - SiC Based Materials
- Key Technology Development for Turbine Airfoils in the SRW Project
 - Small Component Fabrication
 - Ceramic Joining and Integration
 - Sub-Element Testing and Characterization
 - Model Development of Relevant Stresses in the Component
- Summary/Conclusions

SRW Large Civil Tilt Rotor Mission and Requirements



EIS = 2025 (2018 tech)	Cruise > 300 knots
TOGW = 108k lbm	@Alt. \Rightarrow best range
Payload = 90 pass.	Cruise L/D \approx 12
Engine = 4x7500HP	Rotor tip speed
Fuel = 21,000 lbm	650 fps hover
Range > 1,000nmi	350 fps cruise

LCTR Mission: 90 passengers, range: 1000 nmi., cruise speed 300 knots, cruise alt.: 28 k-ft.

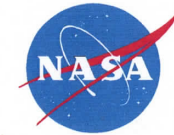
LCTR Engine Characteristics:

7500-8000 HP, overall pressure ratio of 30, T4: 3000°F hover and 2500°F cruise, HPT turbine vane will have dimension of about 1" high and 1" long.

Comparison between the LCTR2 engine and other engines.

Engine	T4 (° F)	Overall Pressure Ratio
V22 (AE1107)	1740	16.7
T700	2600	17
LCTR2 (notional engine)	3000+	30+

SRW Vane Task Overview



Objective:

- Develop technologies for CMC turbine engine components that have higher temperature capability, high fracture toughness, and require less cooling compared to current metallic turbine components.
- Targeted toward the first stage vane (and then blade) of the high pressure turbine (HPT).
- This is a technology development task rather than a component task
- Benefits include: Reduced fuel burn, reduced emissions, lower weight, reduced cooling, and improved efficiency

NASA GRC role vs. industry role: NASA GRC is focused on a cooled HPT (lower TRL) whereas industry may be more focused on less cooled and lower temperature components (higher TRL) in the low pressure turbine (LPT). GRC is focused on the engine requirements of the Large Civil Tilt Rotor Vehicle within the Subsonic Rotary Wing Project.

SRW's CMC effort compared to CMC efforts in other NASA projects (FA and ERA):

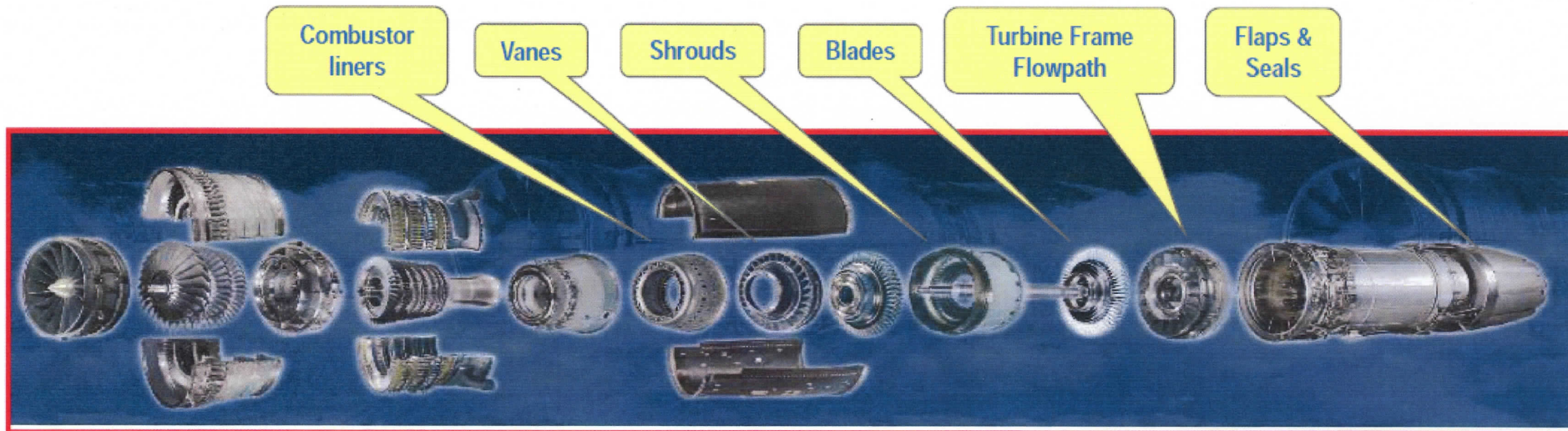
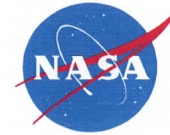
The SRW task is focused on small component fabrication and joining technology development.

All CMC tasks within the projects coordinate with one another to ensure tasks are leveraged and there are no overlaps in efforts.

Challenges:

Fabrication of a small airfoil (1"x1"), cooling schemes, engine operating conditions (i.e. $T_4 > 3000\text{F}$, and $\text{OPR} > 30$), and joining to fabricate the component.

Applications for CMCs in Gas Turbine Engines

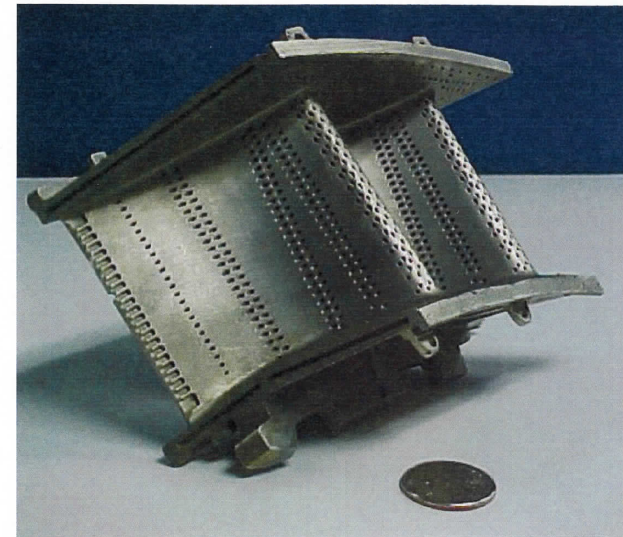
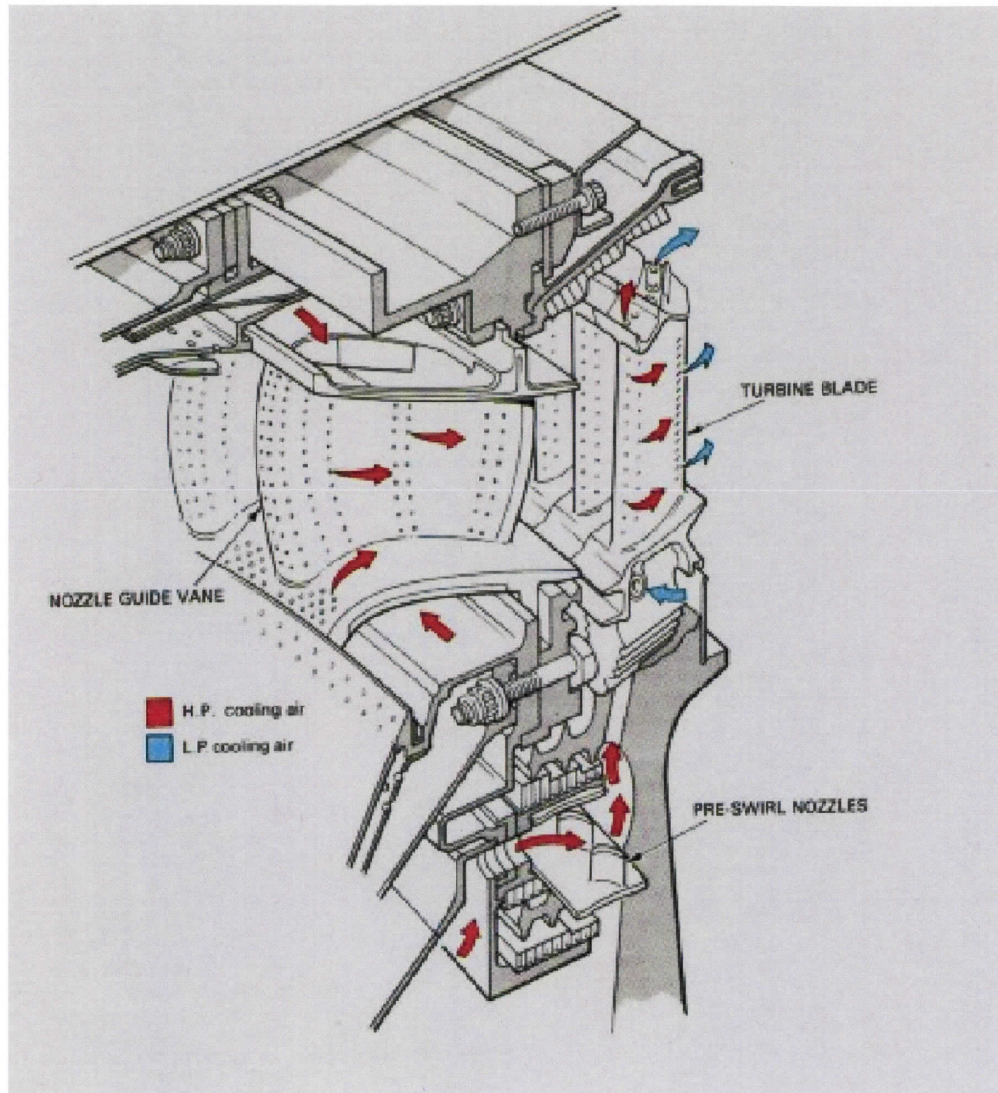
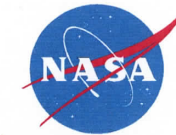


Courtesy of GE Aircraft Engines

Benefits:

- Enabling for high OPR engines (higher turbine inlet temperatures) – reduce cooling air, reduce fuel burn and CO₂ emissions
- Weight = 1/3 of metals and 1/2 of titanium aluminides
- High OPR engines – higher combustor temperature – increased NO_x, CMC combustor liner and first stage turbine vane reduce NO_x

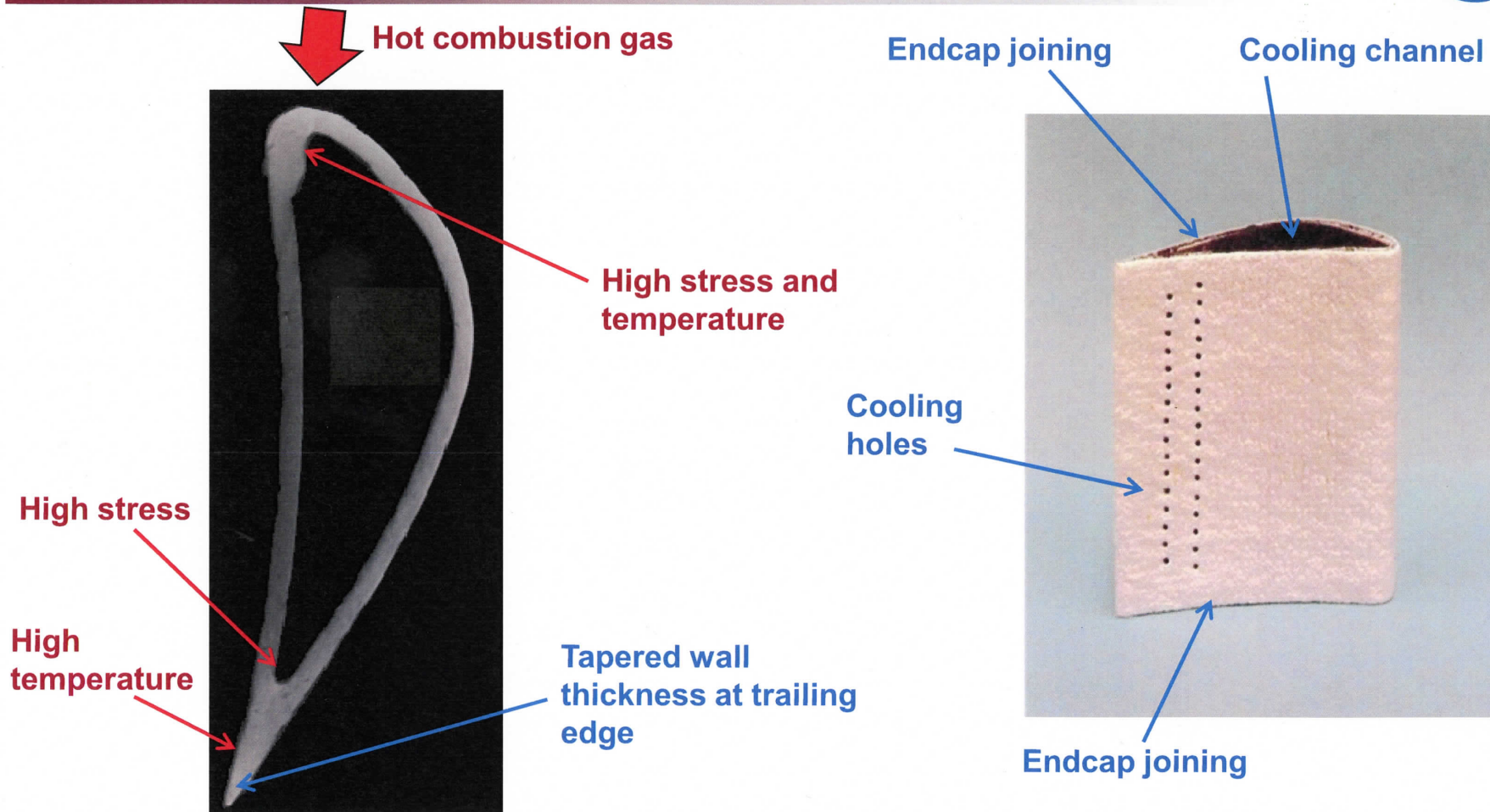
Current Metallic Vane Designs and Cooling Schemes



The preference in CMC turbine component development is to insert the CMC part in-place of the metallic one(s) rather than to drastically alter the outer geometry.

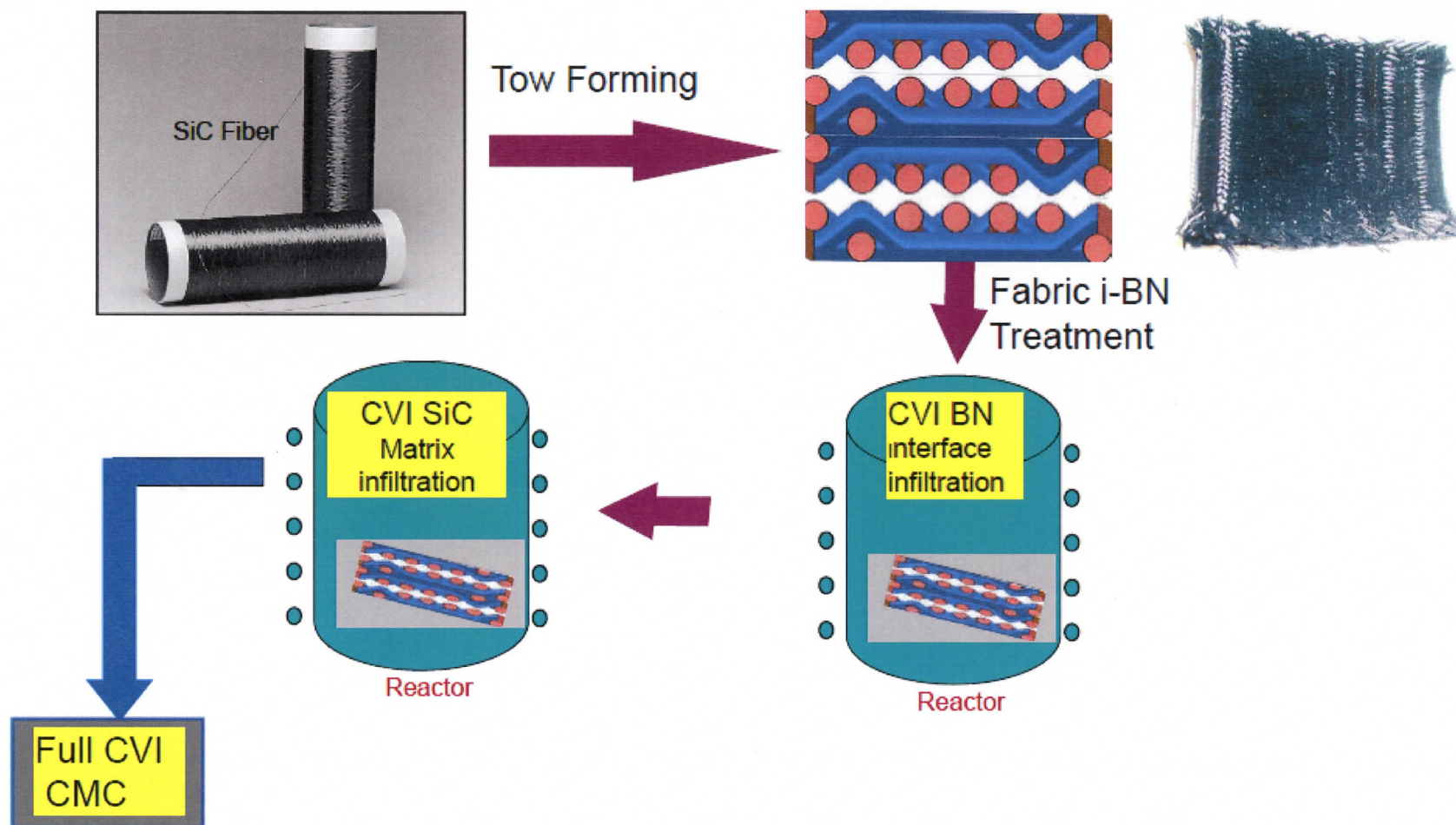
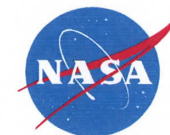
For the SRW effort, the outer geometry is based on T-700 class, 1st stage HPT vane.

Challenges with CMC Vanes and Airfoils



- Production challenges are in fabricating the small radii, the tapered trailing edge, integrating the endcaps, and machining cooling holes.
- Design and material challenges are in meeting the high stress and high temperature requirements, providing sufficient cooling, and having a durable high temperature coating.

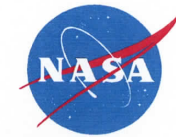
Fabrication Process for Gen III SiC/SiC CMCs (2700° F Capability for G.T. Engines)



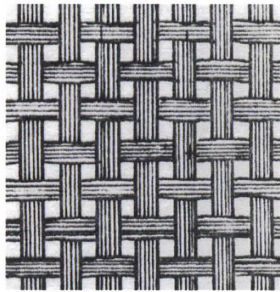
CVI – Chemical Vapor Infiltration

Ceramic Matrix Composite Materials

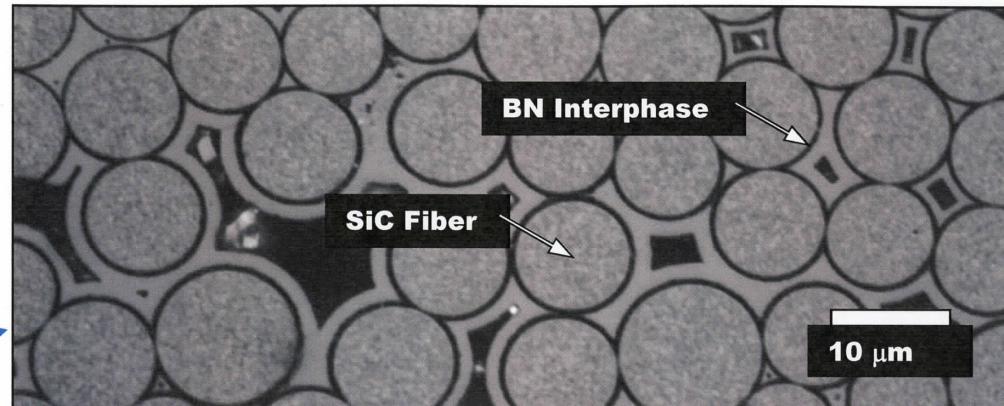
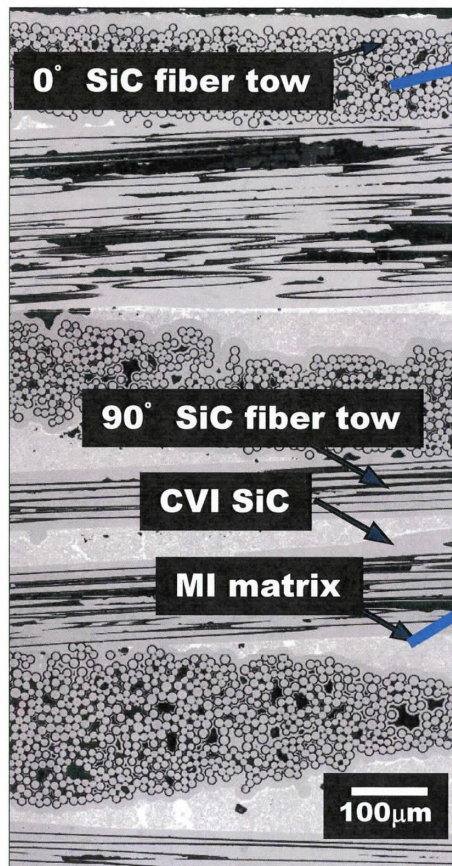
- Melt Infiltrated (MI) SiC/SiC



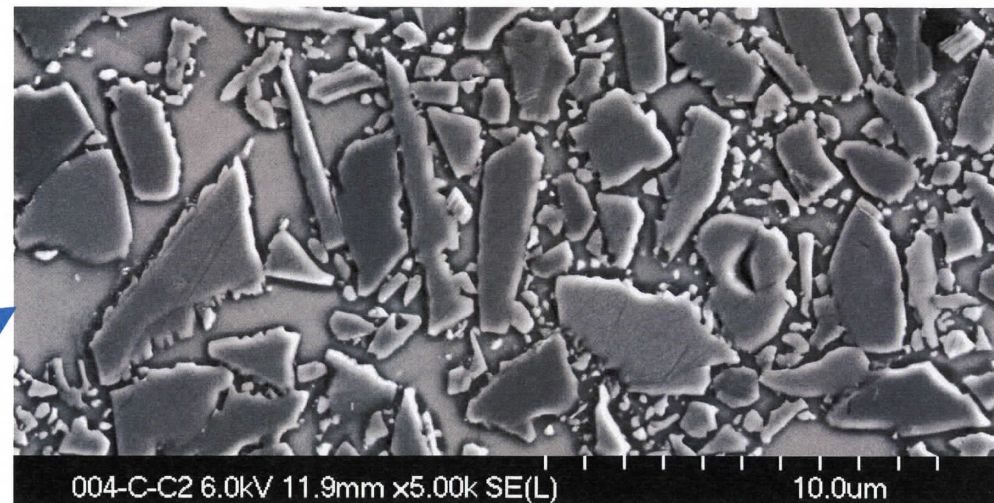
0-90 Plain Fiber
Tow Weave



Composite
Cross-Section



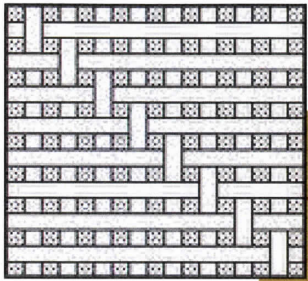
SiC fibers within a tow



SiC grains and silicon within MI matrix

- High thermal conductivity matrix
- Elimination of interlaminar porosity
- No matrix micro cracking

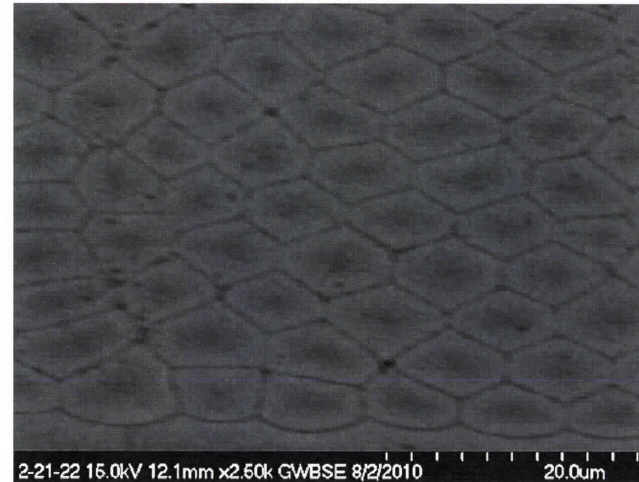
Ceramic Joining and Integration: Commercial High Temperature Ceramic Material - SA-Tyrannohex (SiC Fiber Material)



**8 Harness Satin
Fiber Tow Weave**



Optical Micrograph



SEM Micrograph

Features

- 8 Harness Satin Weave of SiC Tyranno fibers
- Layers hot pressed together
- Hexagonal sintered fibers
- Nano-layer of carbon on the fiber surface

Benefits of SiC SA-Tyrannohex

- High fracture toughness
- Fatigue resistance
- Low weight and high temperature capability
- Machinable and complex shape formation
- Candidate material for the vane endcap

Areas Being Addressed by the SRW Vane Task



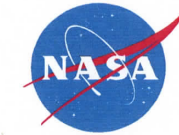
Key Technology Development for a Turbine Airfoil in the SRW Project

Subtasks:

- Small Component Fabrication
- Ceramic Joining and Integration
- Sub-Element Testing and Characterization
- Model Development of Relevant Stresses in the Component

Small Component Fabrication

- Objective and Concepts 1 and 2

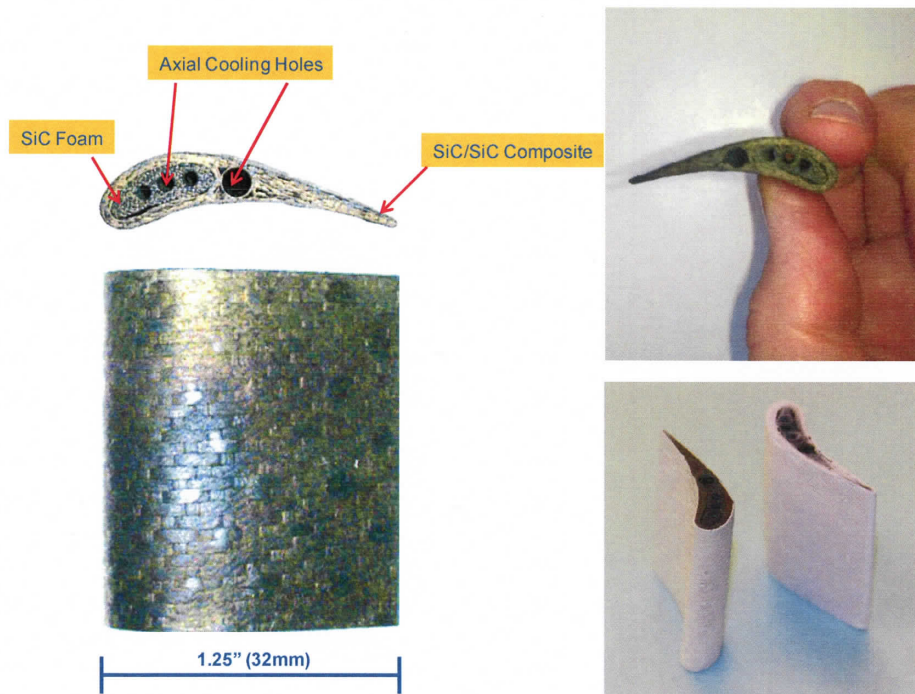


Objective: Demonstrate fabrication ability of small 1"x1" airfoils (vane cord length x height)

Materials: SiC/SiC (w/Sylramic and Hi-Nicalon SiC fibers) CMCs, CMC/ceramic foam hybrid, SA-Tyrannohex as a potential endcap material

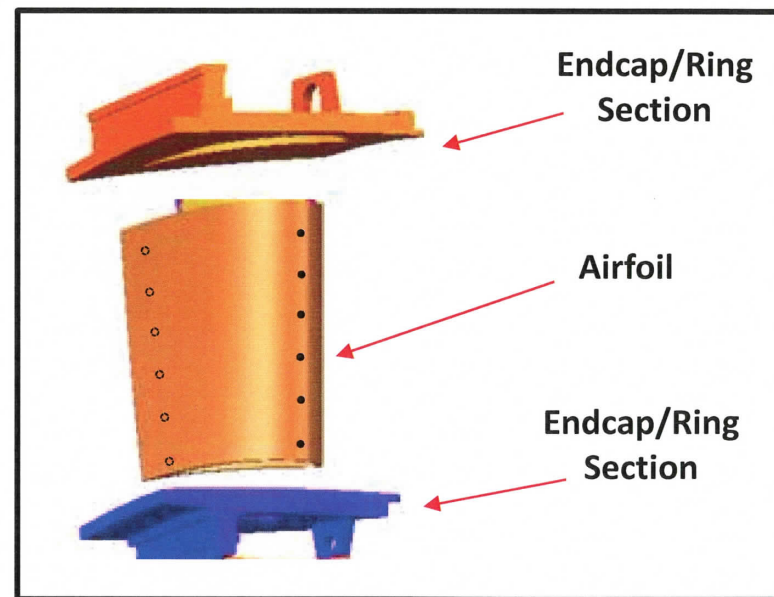
Issues: inter-laminar strength, leading edge, trailing edge, cooling channels, surface cooling holes

Airfoil Concept 1 - Internally Cooled Vane



- Two airfoils sets made with different silicon carbide fibers (Sylramic and Hi-Nicalon-S).
- NASA three layer EB-PVD environmental barrier coatings

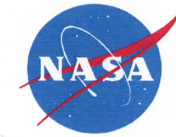
Airfoil Concept 2 - Film Cooled Airfoils for the Vane and Blade



Planned Sub-Element Testing for both Concepts

- Burner rig testing with and without internal cooling and EBC
- Heat flux tests with and without internal cooling and EBC

Ceramic Joining and Integration



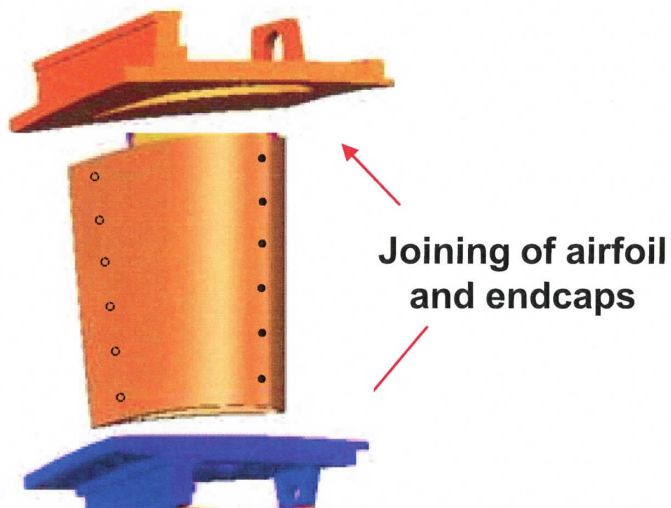
Objective: Develop ceramic to ceramic (and if needed ceramic to metal joining technology)

Materials: SiC/SiC, SA-Tyrannohex, (and superalloys)

Approach: - Develop processing details:

- interlayer
- conditions: time, temperature, and duration
- method: diffusion bonding, brazing, etc.
- Start with ceramic to ceramic joining of simple shapes
- Join more complex shapes
- Characterize and test (i.e. microstructural analysis, mechanical tests, thermal cycling, and burner rig)

Potential Joining Needs



Joining of singlet vanes to form doublets and joining of vane airfoils to ring sections

Ceramic Joining and Integration

- Joining Processes



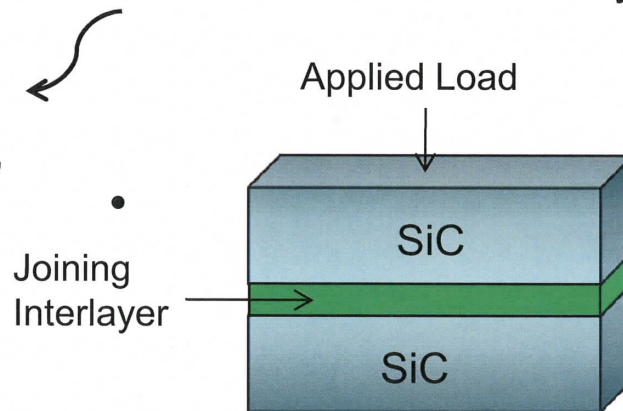
Materials (dimensions 0.5" x 1")

- Substrate: SiC/SiC and SA-TyrannoHex
- Interlayers: Ti foil (10, 20 micron) and B-Mo alloy foil (25 micron)

Diffusion Bonding

- Atmosphere: Vacuum
- Temperature: Ti 1200°C, Mo 1400°C
- **Pressure: 30MPa**
- Duration: Ti 4 hr
B-Mo 4 hr
- Cool down: 2 °C/min

- Ceramic substrates were ultrasonically cleaned in Acetone for 10 minutes
- Substrates were sandwiched around braze and foil layers



Materials (dimensions 0.5" x 0.5")

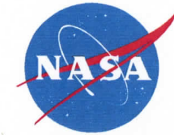
- Substrate: SiC/SiC and SA-TyrannoHex
- Interlayer: pastes and tapes of Si-based eutectics

Brazing

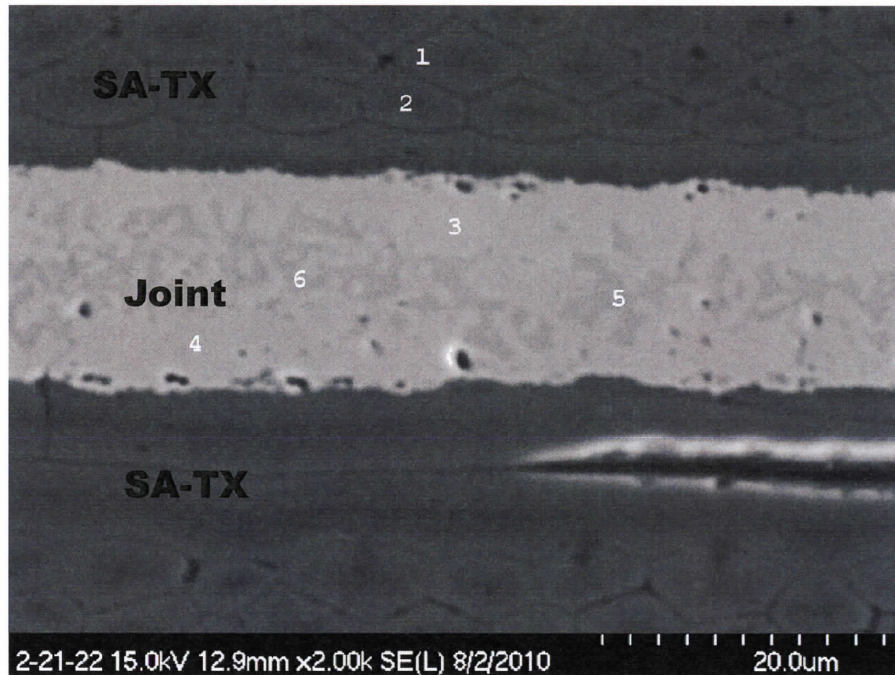
- Atmosphere: Vacuum
- Temperature: 1340°C (10°C above the braze liquidus temperature)
- **Load: 100 g/sample**
- Duration: 10 minutes
- Cool down: 2 °C/min

- Mounted in epoxy, polished, and joints characterized using optical microscopy and scanning electron microscopy with energy dispersion spectroscopy analysis

Ceramic Joining and Integration - Diffusion Bonding with 10 μm Ti Foil and 25 μm B-Mo Alloy Foil



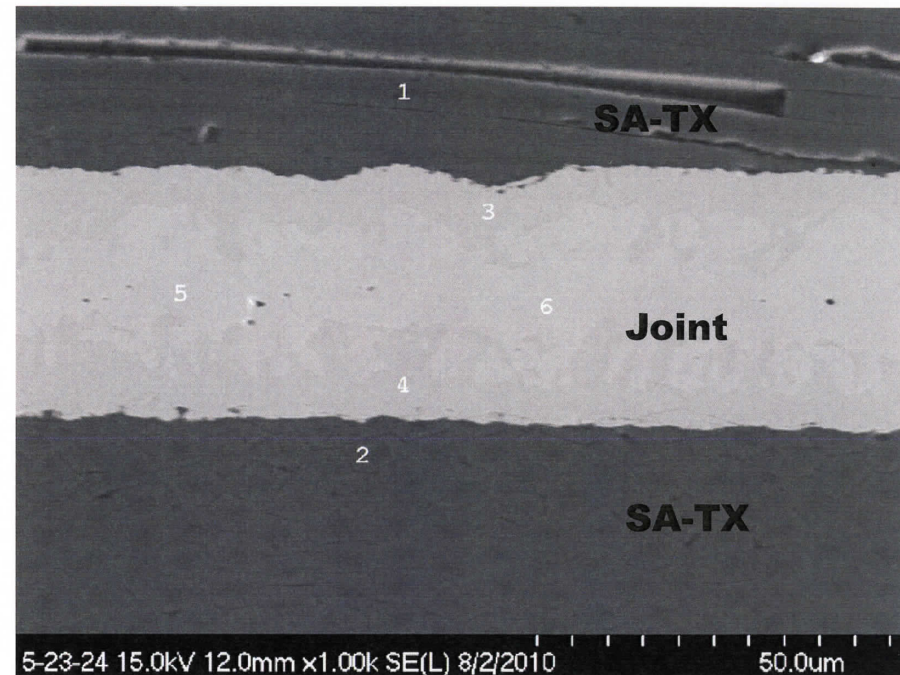
SA-Tyrannohex / Ti / SA-Tyrannohex



	C	Si	Ti
1	54.28%	45.72%	0%
3	44.89%	15.79%	39.33%
5	0%	69.39%	30.61%

Percents are atomic %

SA-Tyrannohex / B-Mo alloy / SA-Tyrannohex



	C	Si	B	Mo	O
1	58.34%	41.66%	0%	0%	0%
3	19.09%	5.51%	63.96%	8.25%	3.19%
5	0%	0%	89.18%	10.82%	0%

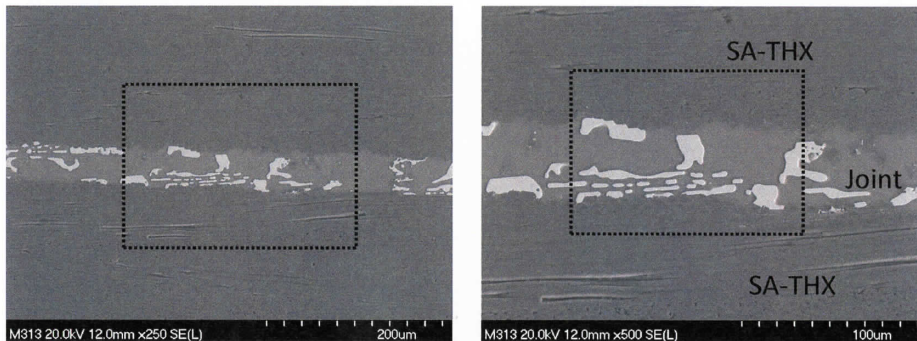
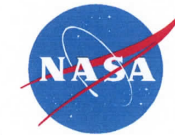
Percents are atomic %

Very good quality bonds are obtained that are uniform and crack free.

However, the joining process requires high applied loads and flat sub-elements for joining.

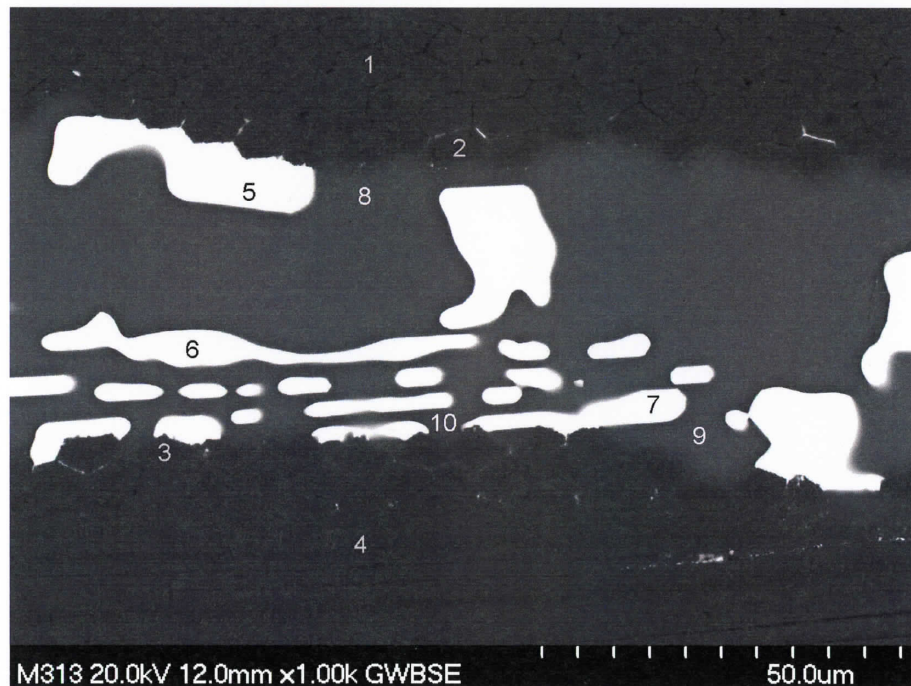
Ceramic Joining and Integration

- Joining with Eutectic Phase Tapes: Microstructure



Brazing with the eutectic phase tape does not require a load and complex shapes can be joined.

Joining of SA-Tyrannohex in the parallel orientation.

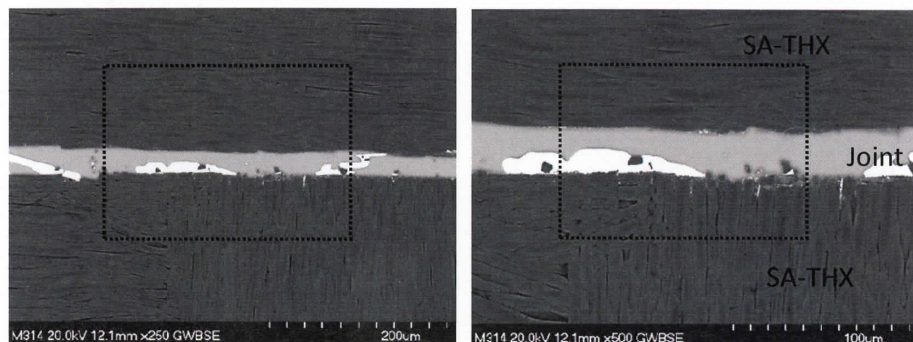
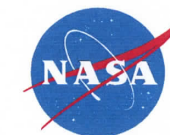


Spot	C	Si	Al	Hf
1	63.12	36.88		
2	64.30	35.70		
3	67.75	32.25		
4	63.82	35.40	0.78	
5	55.93			44.07
6	56.83			43.17
7	55.28			44.72
8	32.89	67.11		
8a		100.00		
9	32.92	67.08		
9a		100.00		
10	32.34	67.66		
10a		100.00		

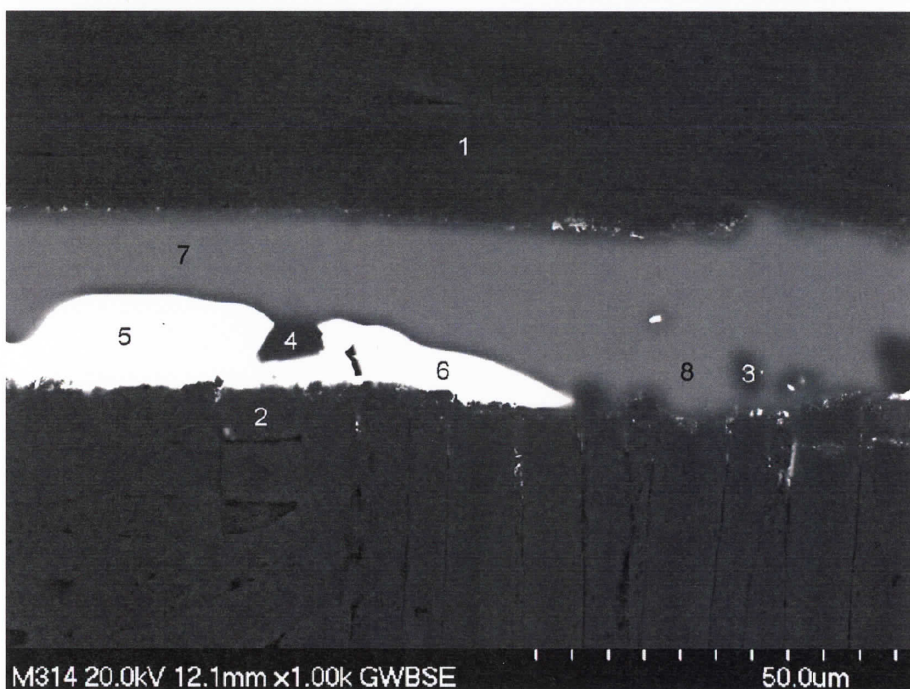
M313: Parallel SA-THX / 1 layer Si-Hf Eutectic tape / Parallel SA-THX. Magnifications of x250 and x500 (top) and magnification at x1000 (w/EDS results) (bottom).

Ceramic Joining and Integration

- Joining with Eutectic Phase Tapes: Microstructure



Joining of SA-Tyrannohex in the perpendicular orientation.

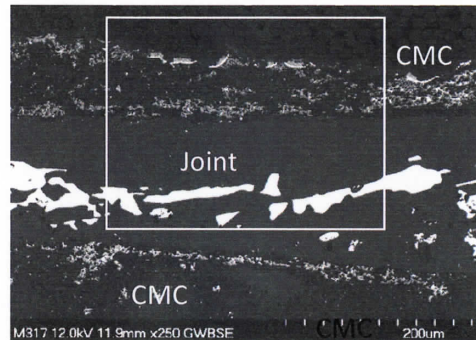


Spot	C	Si	Hf
1	61.71	38.29	
2	61.81	38.19	
3	57.41	42.59	
4	57.63	42.37	
5	53.25		46.75
6	65.12		34.88
7		100.00	
7a	31.28	68.72	
8		100.00	
8a	32.32	67.68	

M314: Perpendicular SA-THX / 1 layer Si-Hf Eutectic tape / Perpendicular SA-THX. Magnifications of x250 and x500 (top) and magnification at x1000 (w/EDS results) (bottom).

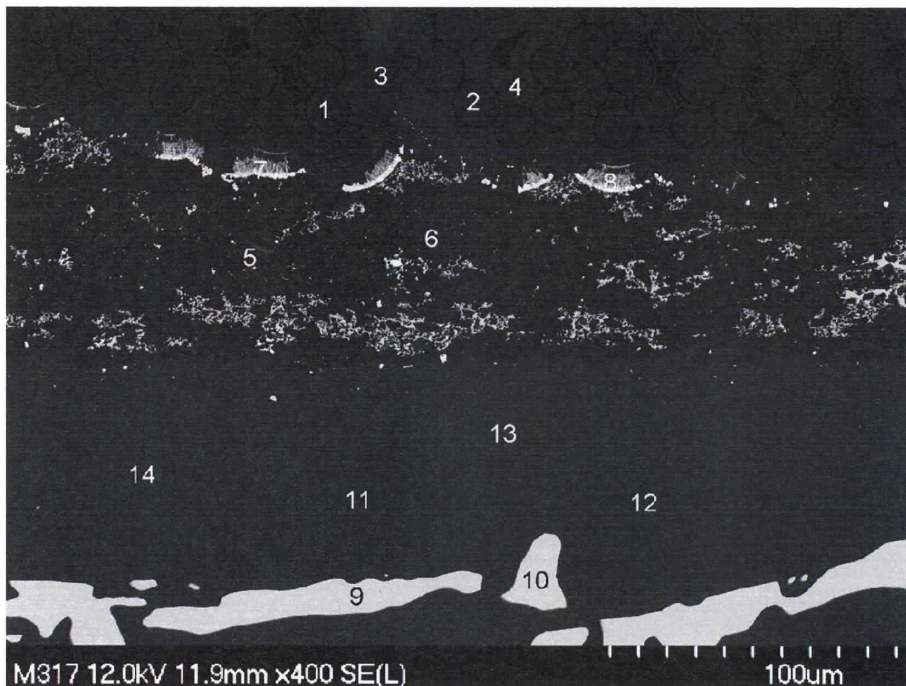
Ceramic Joining and Integration

- Joining with Eutectic Phase Tapes: Microstructure



Joining of melt-infiltration SiC/SiC.

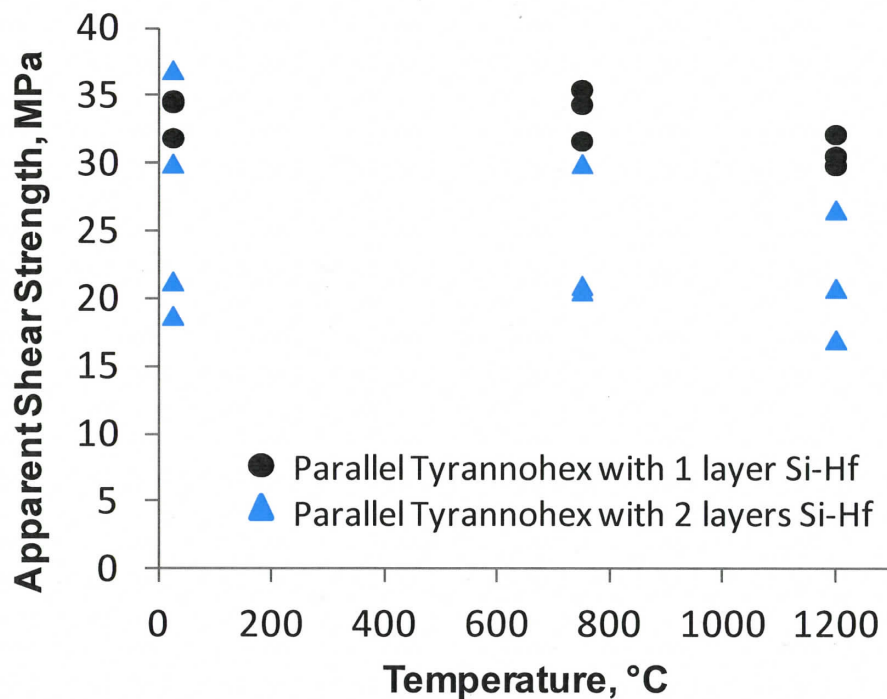
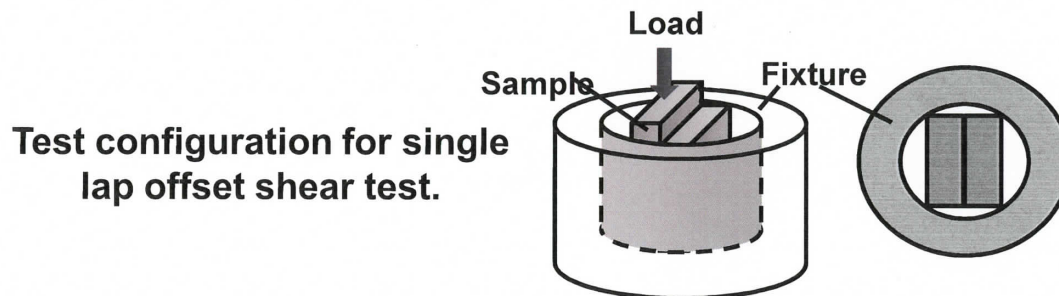
Spot	C	Si	Hf
1	72.62	27.38	
2	72.11	27.89	
3	68.34	31.66	
4	68.89	31.11	
5	66.51	33.49	
6	56.57	43.43	
7	78.06		21.94
8	73.46		26.54
9	72.41		27.59
10	72.04		27.96
11		100.00	
11a	49.96	50.04	
12	49.74	50.26	
13	49.76	50.24	
14	48.90	51.10	



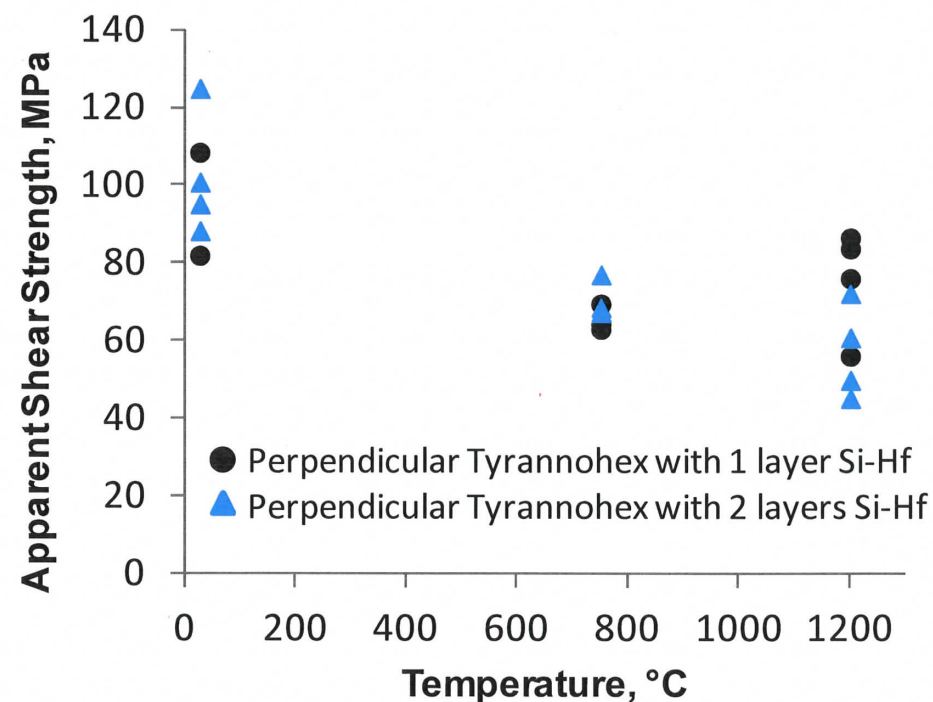
M317: MI SiC/SiC / 2 layers Si-Hf Eutectic tape / MI SiC/SiC.
Magnifications of x250 (top) and x400 (w/EDS results) (bottom).

Ceramic Joining and Integration

- Joining with Eutectic Phase Tapes: Mechanical Tests

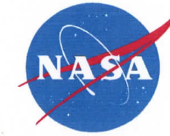


Strengths of parallel Tyrannohex joints.

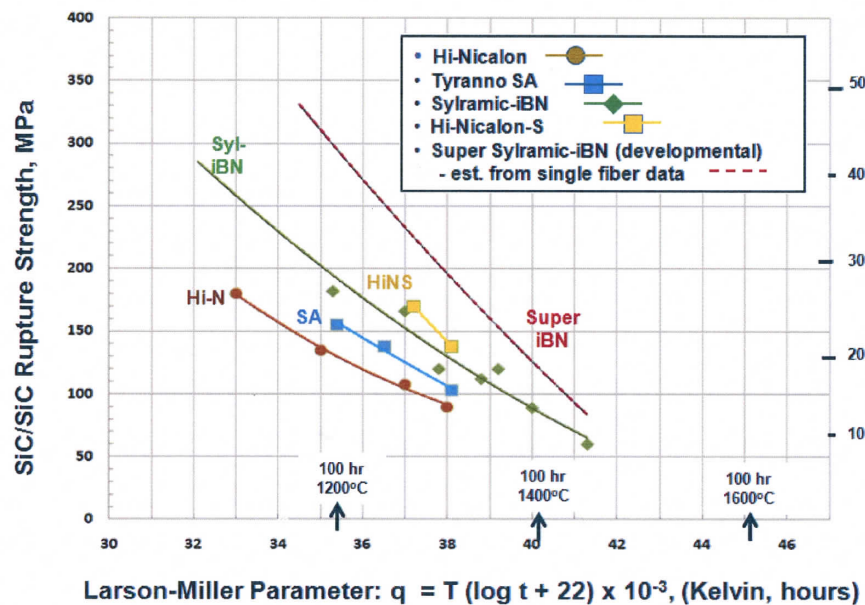


Strengths of perpendicular Tyrannohex joints.

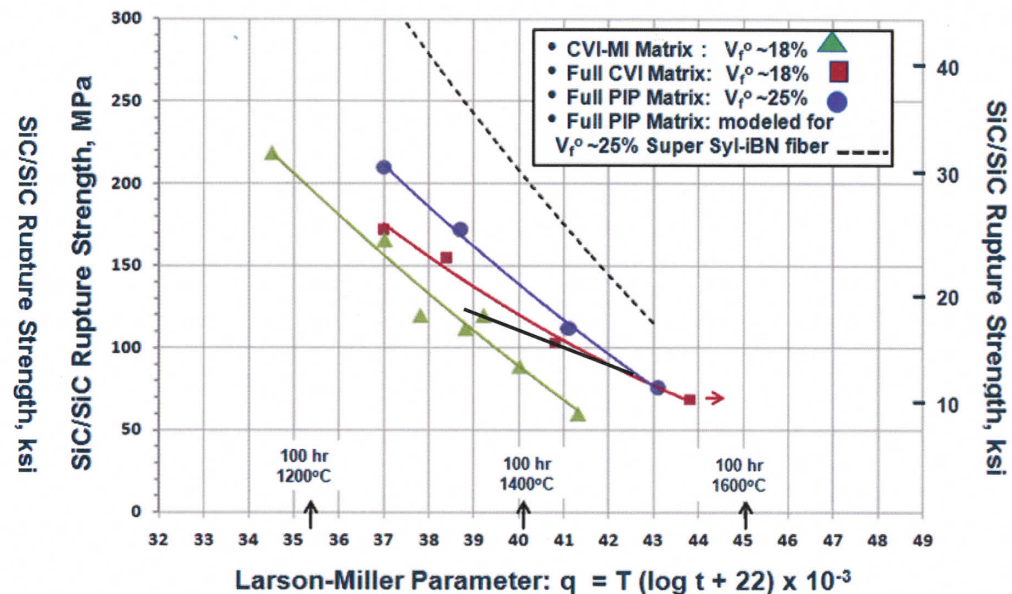
Sub-Element Testing and Characterization



Objective: model and conduct judicious selection of materials; test materials, coated materials, airfoils, and joined sub-elements to evaluate capabilities in more relevant conditions.



Effects on SiC/SiC Rupture Strength Data in Air by Reinforcement of a CVI-MI Matrix with various High-Performance SiC Fiber Types.



Rupture Strength in Air for SiC/SiC CMC with CVI-MI, Full-PIP, and Full-CVI Matrices reinforced by Sylramic-iBN Fibers. Also Tyrannohex SA (—).

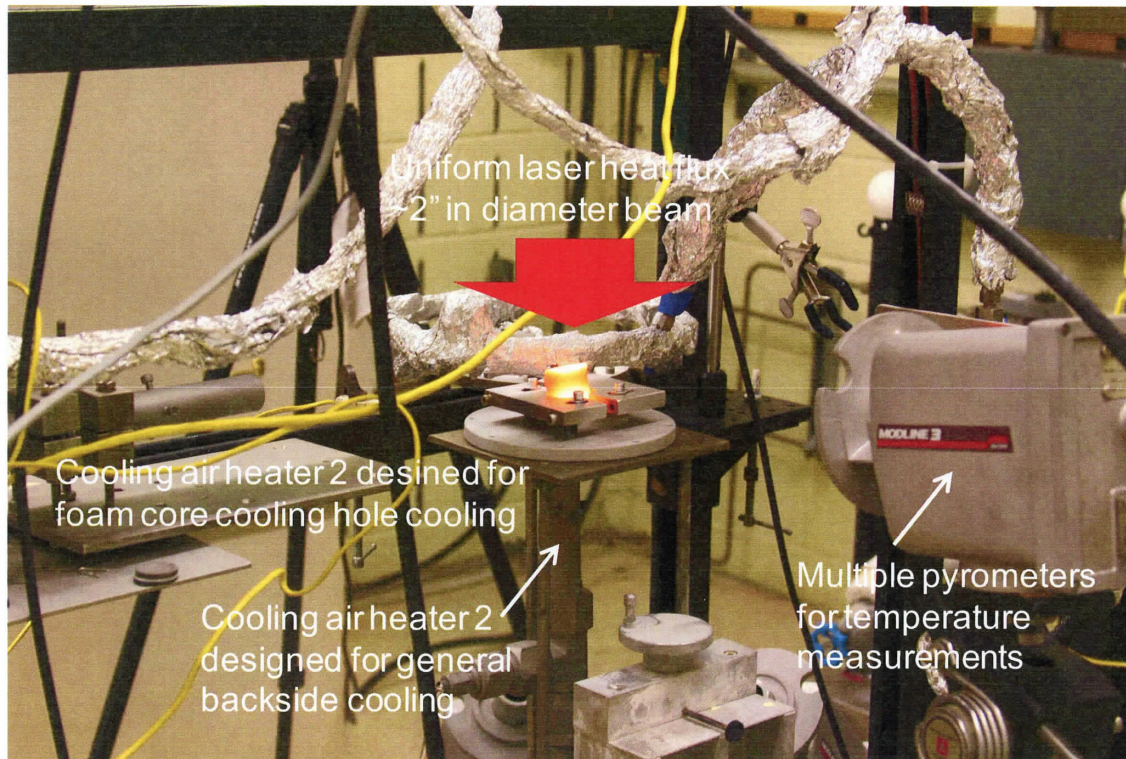
An empirical model will be developed to act as the foundation of a more physics-based mechanistic model and predictive tool for down-selection of the optimum SiC/SiC processes, materials, and microstructures for a CMC HPT vane.

Sub-Element Testing and Characterization

- Laser High Heat Flux Thermal Gradient Tests

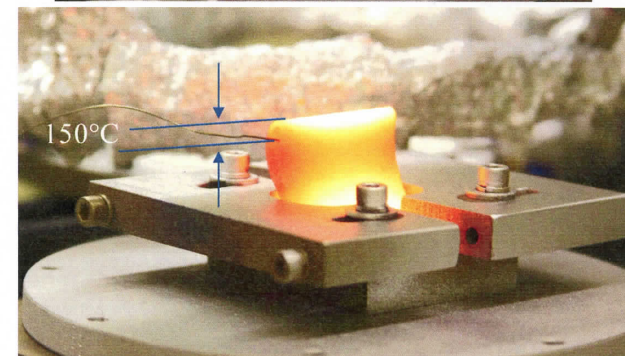
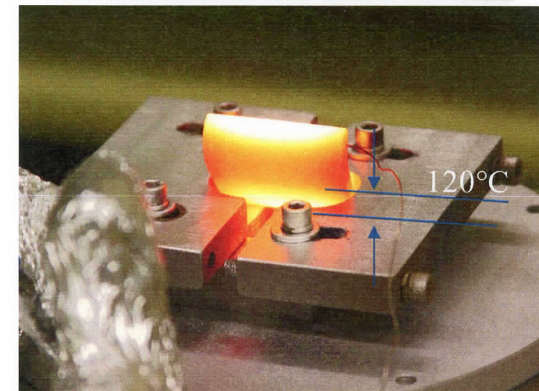
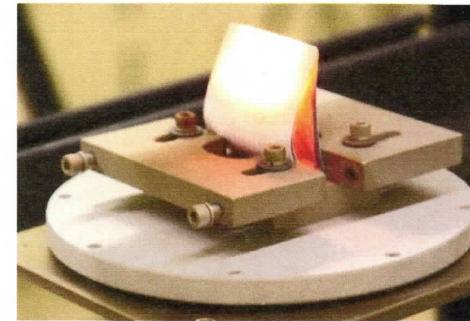


Laser High Heat Flux Thermal Gradient Rig



The rig allows for thermal cyclic tests, steam tests, bi-axial creep tests, and durability tests of coatings and materials.

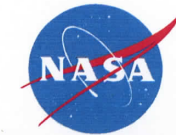
Two cooling air heaters, both are capable of providing up to 815° C (1500F) temperature cooling air, were designed for airfoil foam-core hole cooling air supplies and also for general backside cooling requirements.



Testing of the CMC/foam hybrid in air, using 1 hr cycles, to complete total 50 hrs testing.

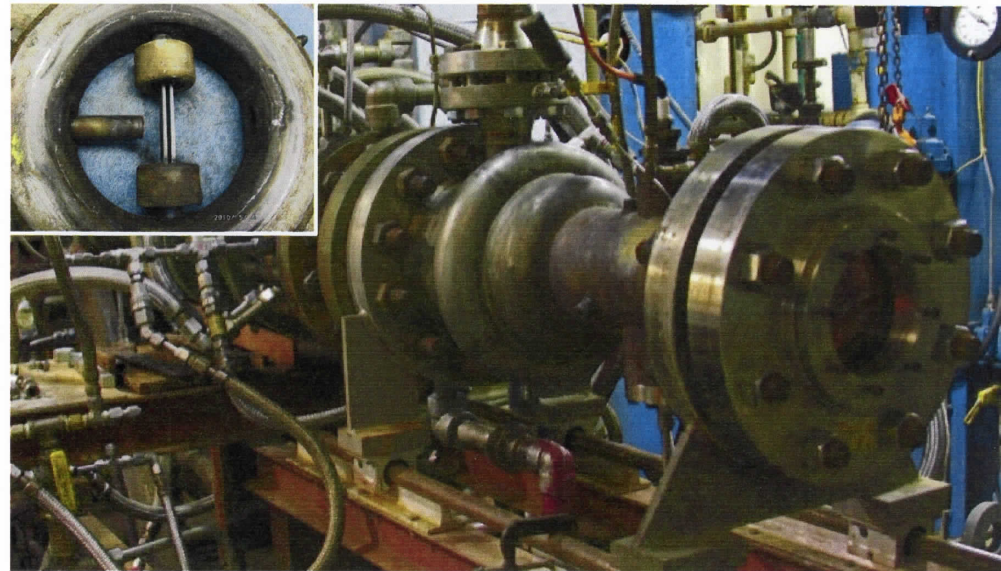
Sub-Element Testing and Characterization

- High Velocity High Pressure Burner Rig: Material Recession

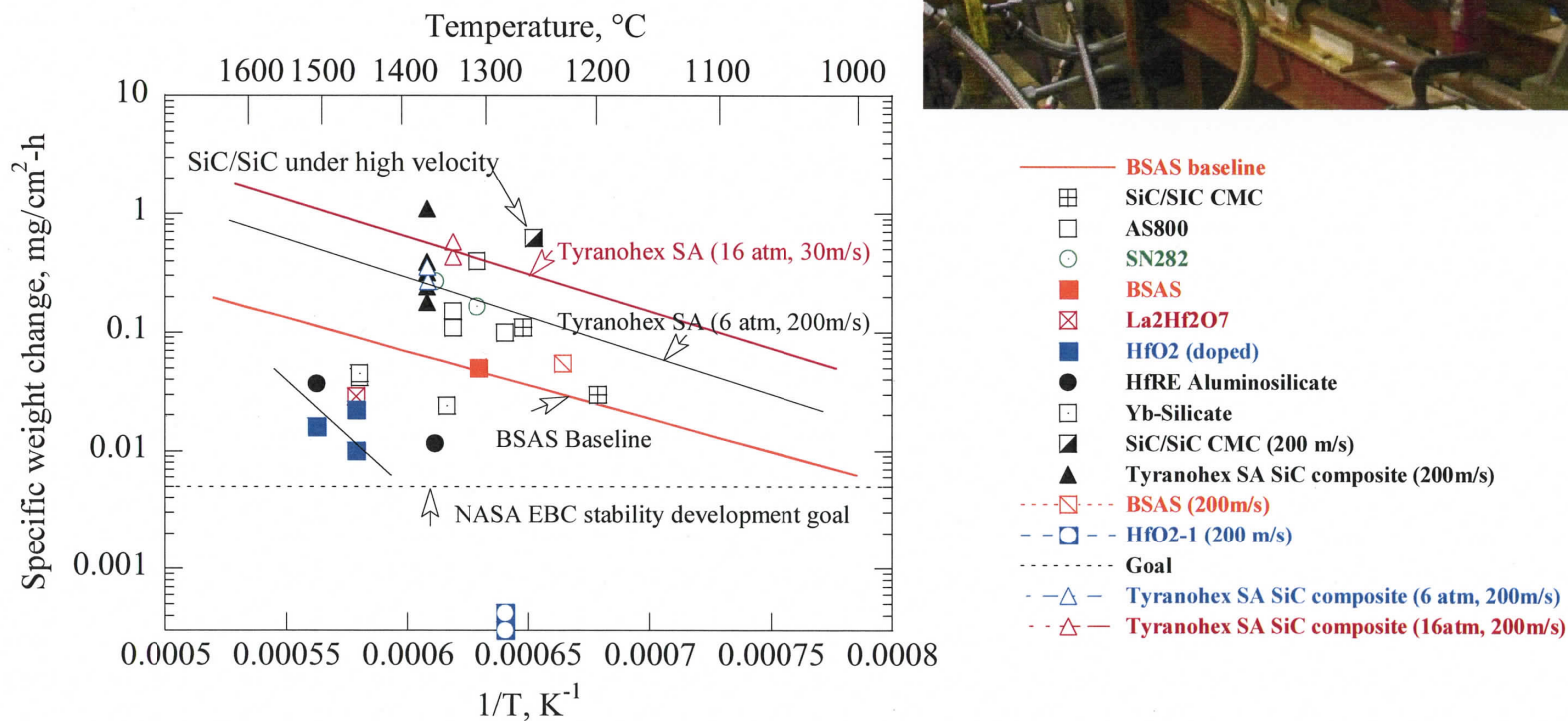


High Velocity High Pressure Burner Rig Recession Tests

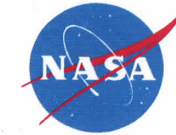
6 -16 atm and 200m/s gas velocity



Recession rates of Tyranno hex SA SiC composite as compared to other ceramic materials. Unlabeled test conditions are standard condition, 6 atm 30 m/s.

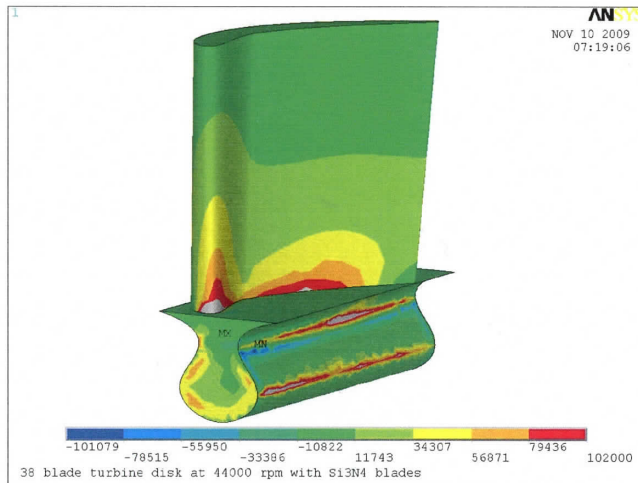


Model Development of Relevant Stresses in the Component

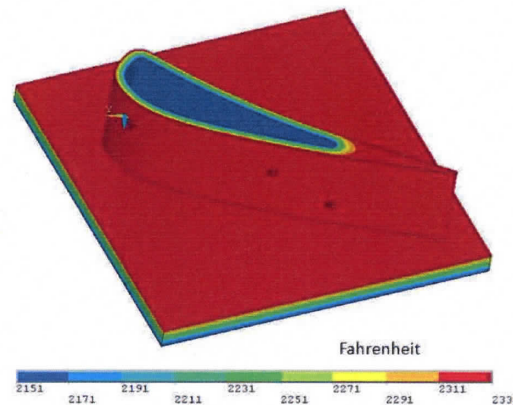


Objective: Investigate design issues for a vane component with emphasis on thermal and mechanical conditionals, material capabilities, and component cooling.

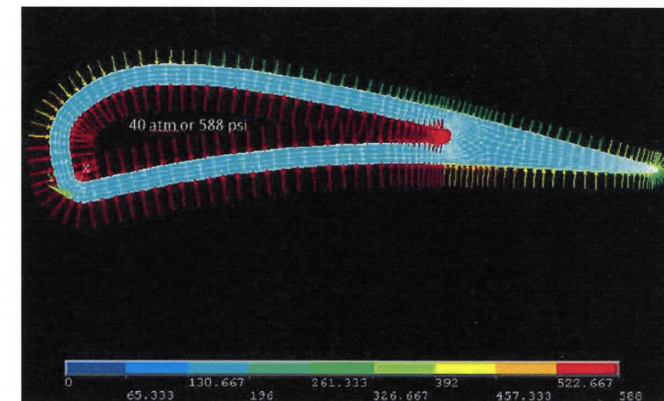
Approach: - In-house: stress analysis on first generation airfoils
- Out-of-house: N&R Engineering Phase 1 and Phase 2 SBIRs.



Blade Stress Analysis for Determination of a Blade versus Vane Task.



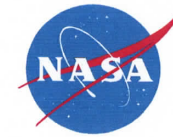
Vane Temperature Distribution (N&R).



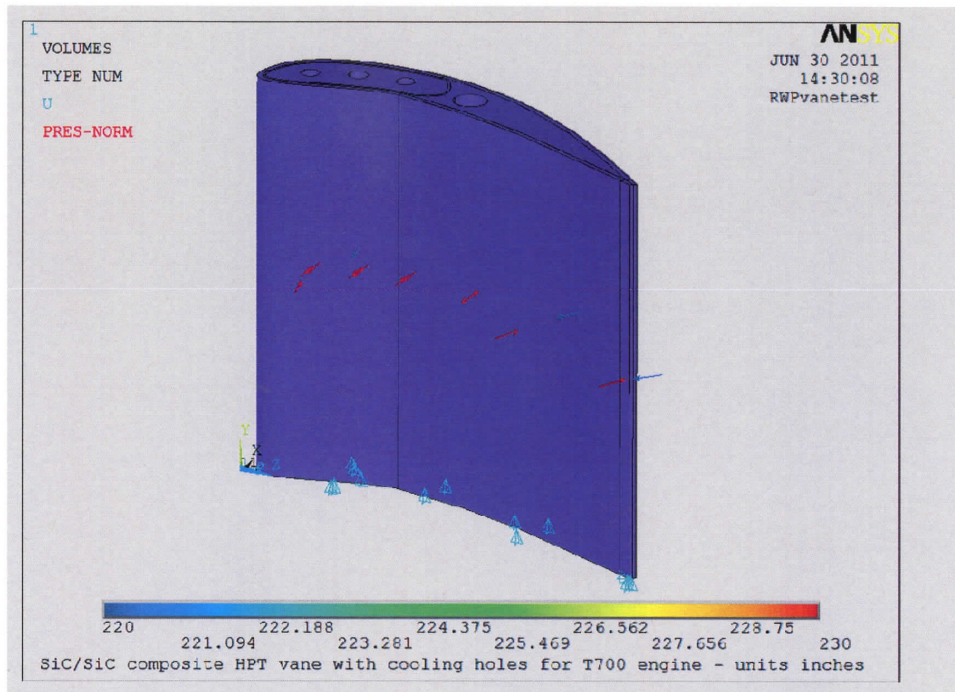
Vane Pressure Loads (N&R).

Model Development of Relevant Stresses in the Component

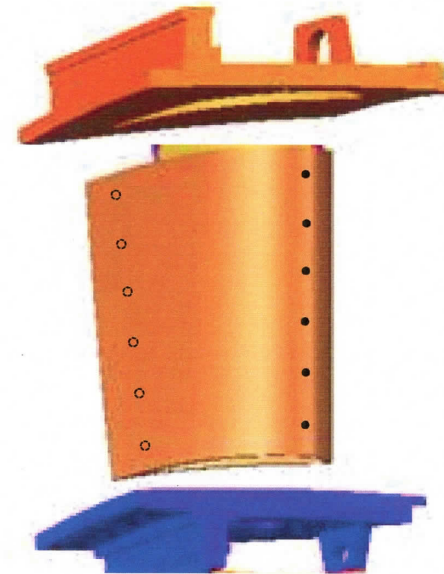
- Thermal and Stress Analysis of Vane Designs



Airfoil Concept #1 - Internally Cooled Vane

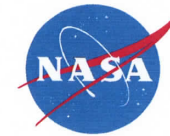


Airfoil Concept #2 - Film Cooled Vane



For the above designs, thermal profiles and loads due to thermal and mechanical stresses will be calculated.

Summary/Conclusions



- CMCs in turbine engine applications offer such benefits as:
 - Reduced fuel burn, reduced emissions, and lower weight
 - Higher temperature capability enables engine operation at higher power density (higher temperature and pressure)
 - Reduced cooling results in improved efficiency
- The SRW Airfoil task is addressing unique challenges the for the LCTR mission and engine class.
- Progress is being made in critical areas to include:
 - Small component fabrication
 - Ceramic joining and integration
 - Material and component testing and characterization
 - Design and analysis of concept components
- The concept sub-components and components with features for study will be demonstrated in challenging conditions that are relevant to the engine conditions.

